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FINAL REPORT FOR A PROGRAM IN AIR TRANSPORTATION TECHNOLOGY (JOINT UNIVERSITY PROGRAM)

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SUMMARY

The Joint University Program on Air Transportation Technology was conducted at Princeton University from 1971 to 1995. Our *vision* was to further understanding of the design and operation of transport aircraft, of the effects of atmospheric environment on aircraft flight, and of the development and utilization of the National Airspace System. As an adjunct, the program emphasized the independent research of both graduate and undergraduate students. Recent principal *goals* were to develop and verify new methods for design and analysis of intelligent flight control systems, aircraft guidance logic for recovery from wake vortex encounter, and robust flight control systems. Our research *scope* subsumed problems associated with multidisciplinary aircraft design synthesis and analysis based on flight physics, providing a theoretical basis for developing innovative control concepts that enhance aircraft performance and safety. Our research *focus* was of direct interest not only to NASA but to manufacturers of aircraft and their associated systems. Our *approach, metrics, and future directions* are described in the remainder of the report.

INTRODUCTION

Air transportation provides the backbone for passenger transport over moderate to long distances in the U.S., and it is becoming an increasingly important mode for short-range travel and cargo transport as well. As a consequence, there is a growing demand for use of available airspace, a heightened concern for safety, and a greater likelihood that poor weather will be encountered during typical flight operations.

Air transportation affects this nation's competitiveness in two ways: 1) It is an important component of the industrial base, having made a positive contribution to our balance of payments for many years, and 2) it is an enabling technology for all other industries, providing a major avenue for commerce by moving both people and cargo. Air transport activity (measured by aircraft operations) is growing at a rate of 2 to 3 percent per year, while passengers flown are increasing at a rate of 4 percent per year (indicating a trend toward larger aircraft). Over 600 million passengers flew a total of 576 billion miles in 1995. Continued improvements in safety and efficiency of civil aviation are urgently needed if we are to preserve not only national competitiveness but the quality of our lives and our environment in the process.

New technologies hold promise for increasing the productivity, reliability, and safety of the air transportation system, but they introduce uncertainty and present new challenges for certification. It is necessary, therefore, to create new ways of dealing with these problems and, in the process, to nurture a new generation of researchers capable of solving problems yet to come.

Background - In 1971, NASA initiated the Joint University Program (JUP) on Air Transportation Technology, which is implemented by research grants to three universities -- the Massachusetts Institute of Technology, Ohio University, and Princeton University. It was intended that the research programs be interactive, especially on a student-to-student basis, and that they should build on the particular strengths inherent in the programs at the separate institutions. The Federal Aviation Administration joined NASA in support of the program in 1983, and the FAA continues to support this program. The goals of this program were consistent with the aeronautical interests of both NASA and FAA in furthering the safety and efficiency of the National Airspace System.

Since then, active programs of education and research at the three universities have provided a strong base on which to build cooperative efforts. Each university submits a separate proposal and is dealt with individually by NASA and FAA. By being identified as participants in a common program, a degree of cooperation and interchange of ideas has been achieved that would not have been possible otherwise. The diversity of interests and capabilities offered by the three universities is an advantage in promoting the broad perspective needed to address air transportation problems.

At the completion of each research task, a comprehensive and detailed report is issued, for distribution to other participants in the program. Typically, this is a thesis that fulfills requirements for a graduate degree or a report describing an undergraduate independent work project. In addition, papers are prepared for technical conferences and archival journals. These not only document work for program participants: they provide visibility for the JUP with national and international audiences.

During the year, a quarterly program review is held at a NASA or FAA center and at each of the three universities. At this time, research results of the past quarter are presented, and future research plans are discussed. In addition, guest lecturers give presentations on matters of common interest. These meetings are attended by students, principal investigators, technical monitors, and other interested parties from government, industry, and academia. Beginning in 1980, the annual government center meeting has been documented in a NASA Conference Publication. This publication contains review papers written by each of the princi-

investigators, as well as charts presented at the meeting (with annotations) and key technical papers from archival journals and technical conferences.

For particular research projects, students may be in residence at one of the other universities or at a government center for a term or a summer, in order that special courses or facilities be made available to them. Such exchanges are conducted in accordance with the normal rules of the host institution. In the past, the JUP has been characterized by great flexibility in responding to the research interests of NASA and FAA and to the educational objectives of the participating universities.

Through the JUP, university principal investigators have explored new and important areas of aeronautical technology. By focusing on a well-defined yet broad area of research, by emphasizing coordinated, individual efforts of students and their professors, and by providing long-term continuity of support, the program has allowed us to develop deep perspectives about aeronautical problems and their solutions.

The three universities are currently conducting cutting-edge research on intelligent flight control systems, weather hazard avoidance, satellite navigation, cockpit displays, and intelligent air traffic management. With a very modest budget, we have granted over 70 graduate degrees and over 60 B.S.E. degrees since inception. The quality of the program is reflected in the fact that our students have won the prestigious William E. Jackson Award of the Radio Technical Commission for Aeronautics 13 out of the 19 times it has been offered.

Research at Princeton - During the first five years of the grant, the research at Princeton concentrated on guidance laws for terminal area air traffic control, with particular reference to the influence of random disturbances (such as winds) and measurement errors (such as radar errors). The influence of aircraft performance on suitable guidance laws for mixed categories of aircraft also was considered. Studies progressed to closed-loop guidance on curved flight paths and the incorporation of intermittent or lagged radio data.

Attention then shifted to coordinate transformations for OMEGA navigation and to the flight testing of a hybrid navigation system incorporating an Ohio University OMEGA receiver, as well as precision dead-reckoning based on magnetic and air data. These studies complemented and supported research at MIT and Ohio on traffic control theory, runway capacity, curved path following, and radio navigation, and they supported the interests of NASA as evidenced in the Terminal Configured Vehicle and General Aviation Aircraft Programs.

In later years, there was a broadening of the subjects addressed in the research at Princeton. In addition to matters pertaining to navigation and guidance, research was conducted on ultrasonic altimetry, laser-based collision avoidance systems, flying qualities and fuel-use characteristics of small aircraft, fiber-optic data transmission within an aircraft, use of voice recognition in the cockpit, and technical and institutional issues in the development of future general aviation aircraft. More recently, attention has been directed at computer-aided aircraft and control system design, effects of control limitations on closed-loop characteristics of relaxed stability aircraft, flying hazards associated with penetration of wind shear, aeronautical applications of artificial intelligence and neural networks, control system robustness.

Research results from this program have had significant impact on air transportation technology and have helped FAA and NASA formulate plans for future programs. One notable example is our work on the hazards of low-altitude wind shear to takeoff and landing operations. Our research has dealt with avoidance of microbursts using expert systems for decision making, optimal flight paths through unavoided microbursts, and control for the prevention of attitude upset during encounter with a horizontal wind rotor. Princeton's research on real-time applications of artificial intelligence to aircraft control has been trend-setting. Our innovative approach to evaluating the robustness of control systems is likely to have a long-term impact on the analysis and design of flight control systems.

OVERVIEW OF RECENT RESEARCH

Intelligent Flight Control Systems - The capabilities of flight control systems can be enhanced by designing them to emulate functions of natural intelligence. Intelligent control functions fall in three categories. *Declarative* actions involve decision-making, providing models for system monitoring, goal planning, and system/scenario identification. *Procedural* actions concern skilled behavior and have parallels in guidance, navigation, and adaptation. *Reflexive* actions are spontaneous, inner-loop responses for control and estimation. Intelligent flight control systems learn knowledge of the aircraft and its mission and adapt to changes in the flight environment. Cognitive models form an efficient basis for integrating "outer-loop/inner-loop" control functions and for developing robust parallel-processing algorithms.

Intelligent flight control design draws on two apparently unrelated bodies of knowledge. The first is rooted in classical analyses of aircraft stability, control, and flying qualities. The second derives from human psychology and physiology.

The design goal is to find new control structures that are consistent with the reasons for flying aircraft, that bring flight control systems to a higher level of overall capability.

In a classical flight control context, declarative functions are performed by the control system's *outer loops*, and reflexive functions are performed by its *inner loops*. At an intermediate level, *procedural functions* -- like reflexive functions -- have well-defined input-output characteristics but of a more complicated structure. Traditional design principles suggest that the outer-loop functions should be dedicated to low-bandwidth, large-amplitude control commands, while the inner-loop functions should have high bandwidths and low-amplitude actions. There is a logical progression from the sweeping, flexible alternatives associated with satisfying mission goals to more local concerns for stability and regulation about a desired path or equilibrium condition.

An intelligent flight control structure (Fig. 1) has *super-blocks* identifying declarative, procedural, and reflexive functions; these contain the classical GNC functions plus new functions related to decision-making, prediction, and learning. The black arrows denote information flow for the primary GNC functions, while the gray arrows illustrate the data flow that supports subsidiary adjustment of goals, rules, and laws.

Within the super-blocks, higher-level functions are identified as conscious, preconscious, and subconscious attributes as a working analog for establishing a computational hierarchy. The new functions relate to setting or revising goals for the aircraft's mission, monitoring and adjusting the aircraft's systems and subsystems, identifying changing characteristics of the aircraft and its environment, and applying this knowledge to modify the structures and parameters of GNC functions.

The computational analogs of the three cognitive/biological paradigms are expert systems, stochastic controllers, and neural networks. Expert systems organize decision-making efficiently, stochastic controllers optimize estimation and control, and neural networks provide rapid, nonlinear, input-output functions. It appears that many functions at all levels could be implemented as neural networks. While this may not always be necessary or even desirable using sequential processors, mapping declarative and procedural functions as neural networks may prove most useful as a route to new algorithms for the massively parallel processors of the future.

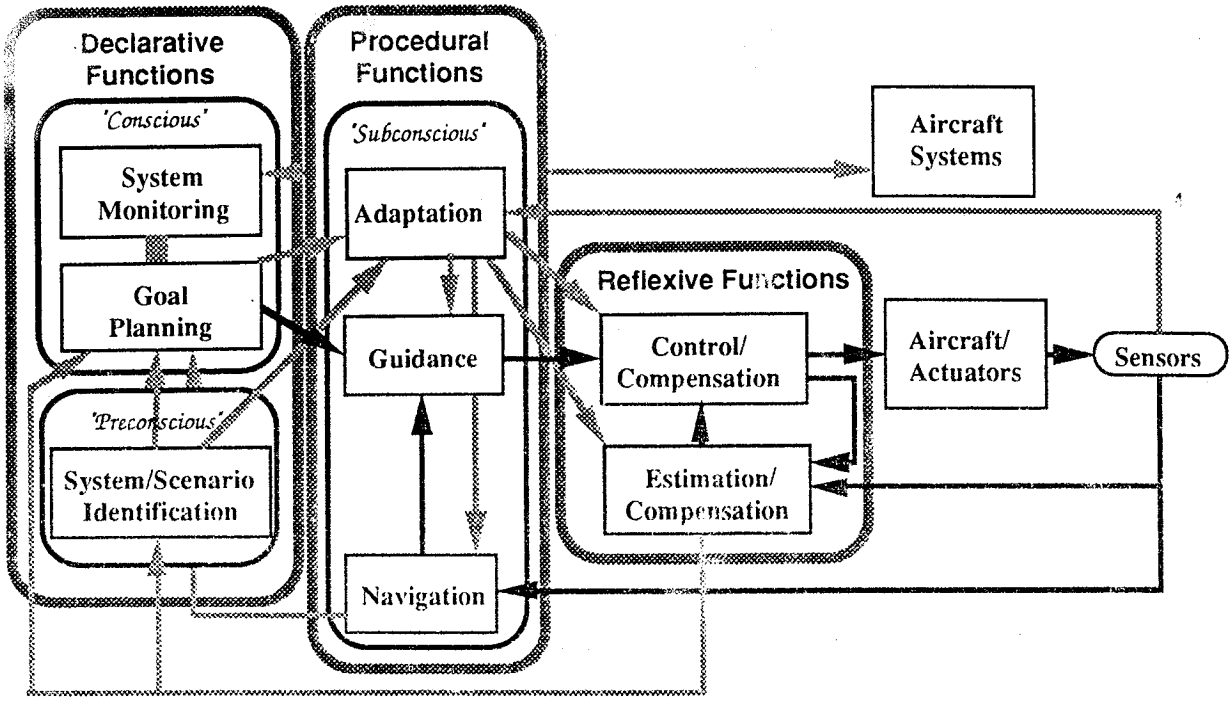

Figure 1. Block Diagram of an Intelligent Flight Control System.

Dynamics and Control of Aircraft Wake Vortex Encounter - Our research began with the study of optimal flight paths for jet transports and general aviation aircraft encountering microburst wind shear. It evolved through the development of an expert system to advise the cockpit crew on avoiding wind shear to defining guidance and control logic for microburst encounter.

The dynamic response of a twin-jet transport aircraft encountering a single-axis wind vortex (Fig. 2 and 3) on final approach to landing also was investigated. A horizontal wind vortex, or wind rotor, is formed by strong winds that flow over a mountain range, "rolling" over the leeward side of the mountain. Severe performance degradation and possible ground impact may result from a low-altitude encounter with a wind rotor. Dynamic simulations determined the effects of vortex strength, vortex length, lateral entry position, vertical entry position, and encounter incidence angle on the aircraft roll response parameters. Simulations revealed the significant hazard produced by the wind-induced moments. These moments arise from spatial gradients acting over the aerodynamic surfaces and by the vortical-velocity components that are strongest near the vortex core radius.

Results showed that maximum roll rate and roll angle increase proportionally with vortex strength and vortex length, until a "saturation length" is reached. Roll response is highly dependent on entry location: changes in lateral entry position affect maximum roll angle while changes in vertical entry position affect max-

imum roll rate. Peak roll rate and roll angle obtain their largest values at near-zero incidence angles. This research culminated with the development of flight control laws that have the potential to dramatically reduce the wind-rotor hazard.

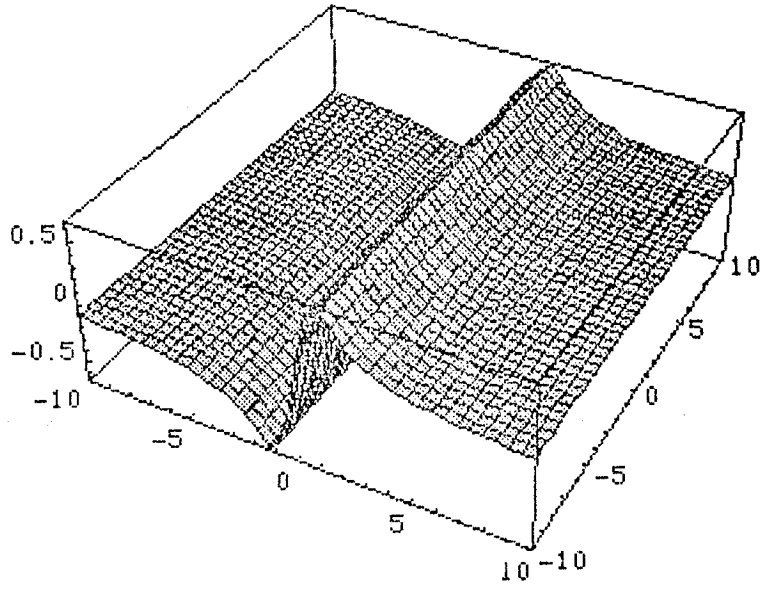

Figure 2. Radial distribution of tangential wind velocity along a line vortex.

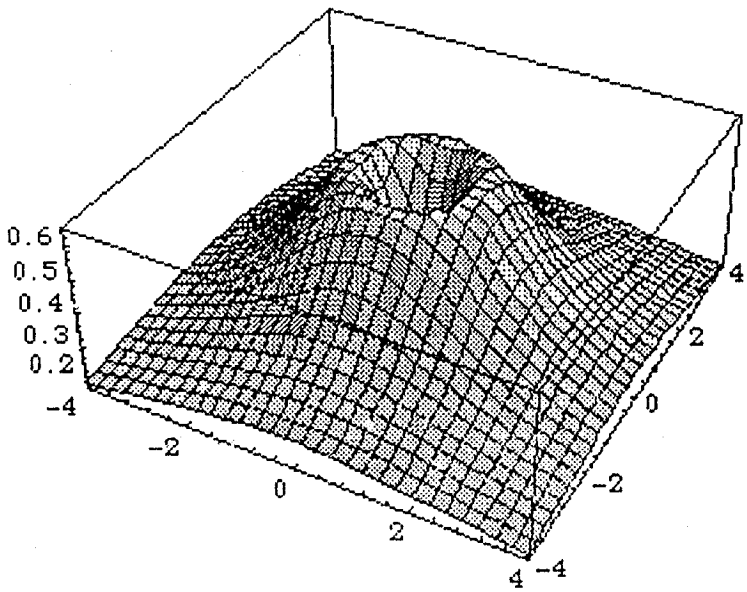

Figure 3. Spatial distribution of wind tangential velocity about the rotor axis.

Robust Flight Control Design - Perfect models of aircraft dynamics are rarely available when controllers are being designed, parameters of similar aircraft are likely to vary from one tail number to the next, and dynamic characteristics may change as parts wear or operating points shift. Flight control system designs must be tolerant of these differences for practical control to take place, that is, they must be *robust.*

Control system robustness is related to aircraft dynamic uncertainty rather than to disturbance input or measurement error uncertainty, and it is an inherently nonlinear problem. Small parametric variations may have effects that are locally linearizable, allowing robustness to be expressed by conventional stability and performance margins. However, it is easy to postulate systems where measures of robustness based on nominal margins fail (e.g., a two-mode system in which the first mode is certain and determines the stability margin, but the second mode is uncertain and becomes unstable for arbitrarily small parameter variations). In such case, robustness can be expressed only by measures based upon the perturbed system itself, evaluated over the full range of possible variations.

Stochastic Robustness Analysis and Design (SRAD) uses statistical descriptions of parameter uncertainty and numerical evaluation to determine whether stability and performance robustness criteria are met (Fig. 4). One important conclusion of our research to date is that there is little correlation between classical stability margins and the likelihood that plant parameter variations lead to instability. The principle reason is that parameter variations change the *shape* of the Nyquist plot as well as the gain and phase margins; hence, the branch of the nominal Nyquist plot or critical frequency that determines stability margins may not be the one that produces instability as parameters vary. The failure of gain and phase margins for the scalar case calls into question the use of singular values as measures of stability robustness for multi-input/multi-output systems, because transfer-function amplitude ratio is equivalent to the singular value in the scalar case. Furthermore, our research has shown that numerical search to minimize stochastic robustness criteria is a practical design method that leads to controllers with the necessary degree of stability and performance robustness.

Recent improvements in the search process -- based on genetic and clustering algorithms -- have yielded a factor-of-20 speedup in control design computations. Future research will incorporate parallel supercomputers for this task. Unlike most current applications of parallel computers in computational fluid and structural analysis, computational speedup for Monte Carlo evaluation should be linear in the number of available processors. It appears that application of parallel computers to Monte Carlo evaluation is itself a new area that has not been widely studied.

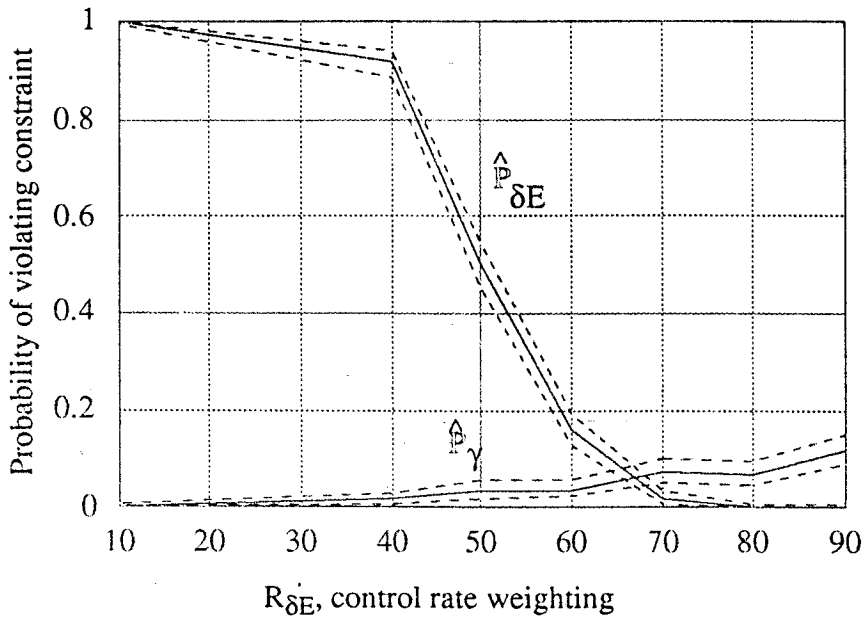

Figure 4. Example of robustness evaluation with Proportional-Filter-Implicit-Model-Following control law. Probabilities of violating flight-path-angle command response and elevator displacement envelopes as functions of control-rate weighting.

SUMMARY OF RESEARCH, 1993-1994

The Air Transportation Technology Program at Princeton University proceeded along four avenues during the final year:

- Microburst Hazards to Aircraft
- Wind Rotor Hazards to Aircraft
- Flight Control System Robustness
- Intelligent Aircraft/Airspace Systems

This research resulted in a number of publications, including theses, archival papers, and conference papers. An annotated bibliography of publications that appeared between June 1993 and June 1994 appears at the end of this report. The research that these papers describe was supported in whole or in part by the Joint University Program, including work that was completed prior to the reporting period.

Severe downdrafts and resulting high velocity outflows caused by microbursts present a significant hazard to aircraft on takeoff and final approach. *Microbursts*, which are often associated with thunderstorm activity, also can occur in the vicinity of dissipating convective clouds that produce no rainfall at ground level. Microburst encounter is a rare but extremely dangerous phenomenon that accounts for one or two air carrier accidents and numerous general aviation accidents each year (on average). Conditions are such that an aircraft's performance envelope may be inadequate for safe penetration unless optimal control strategies are applied.

An expert system for wind shear avoidance that extends the FAA Microburst Windshear Guidelines to account for temporal and spatial variations in wind shear was developed in prior research. Measurements made by a look-ahead sensor (e.g., Doppler radar or lidar) are processed by extended Kalman filters to develop a head-tailwind profile. An archival paper describing the wind-shear estimator was published during the period [1].

Real-time guidance for the case in which wind shear encounter has been encountered was being investigated. Our emphasis shifted from optimal strategies for abort and recovery [2, 3] to strategies based on nonlinear-inverse-dynamic controllers [4]. The former approach seeks to minimize a path-following cost function that implicitly maximizes the minimum altitude during an aborted approach to landing. The latter approach prescribes a desired rate of climb once an abort has been declared, then generates the necessary control commands by inverting the aircraft's dynamic model.

The dynamics and control of a twin-jet transport encountering an intense wind "rotor" were studied [5]. It was found that a physically realizable rotor could roll the aircraft to inverted attitude if left unopposed by lateral control. Similarly, unopposed full rudder deflection could invert the aircraft in its landing configuration. Conventional linear-quadratic flight control laws can maintain wings level through such encounters.

A new effort has begun to characterize the dynamics and control of following-aircraft response to leading-aircraft wake vortices. An aerodynamic model for a subsonic jet aircraft exposed to vortical flows will be developed, concentrating on the resultant forces and moments arising from rotating wind velocity distributions. Methods for designing feedback control logic that use available control power to minimize the disturbance to the following aircraft's flight path will be derived. This logic will combine features of optimization and nonlinear-inverse-dynamic control theory to synthesize practical digital control structures.

Control system robustness is defined as the ability to maintain satisfactory stability or performance characteristics in the presence of all conceivable system parameter variations. While assured robustness may be viewed as an alternative to gain adaptation or scheduling to accommodate known parameter variations, more often it is seen as protection against uncertainties in plant specification. Consequently, a statistical description of control system robustness is consistent with what may be known about the structure and parameters of the plant's dynamic model. Rarely will there be a single "most robust" controller, as design tradeoffs must inevitably be considered. For example, stability, settling time, and control usage all may be of concern; controllers that favor one criterion over the other two have dramatically different characteristics.

Our initial research focused on probabilistic analysis of the stability and performance robustness of given controllers, while more recent research has shifted to designing robust controllers [6]. Numerical search using a genetic algorithm produces robust controllers based on proportional-filter linear-quadratic regulators with implicit model-following. These controllers compare favorably to others designed by competing methods (e.g., those that minimize H_∞ cost functions). This research is proceeding with applications to nonlinear control system design and with the incorporation of parallel processors to speed computations.

Advanced concepts for air traffic management are being developed by modeling aircraft and air traffic centers as intelligent agents that engage in principled negotiation [7]. Each agent is characterized as a dynamic system that carries out declarative, procedural, and reflexive functions [8, 9]. Principled negotiation entails the proposal of alternative flight plans, evaluation of costs and constraints according to separate and shared interests, and conflict resolution. We are setting the groundwork for an *Intelligent Aircraft/Airspace System* (*IAAS*). The goal is to identify means by which ground-based and airborne flight management systems can cooperate to produce a net gain in the efficiency and robustness of air transportation.

Prior research on modeling an aircraft's aerodynamic characteristics using neural networks was reported in an archival paper during the period [10]. It is shown that neural networks provide a promising means of representing aerodynamics for adaptive control and flight simulation.

Two doctoral theses were completed during the period. Sandeep Mulgund developed near-optimal nonlinear guidance logic for aircraft encountering microburst wind shear [11]. Dennis Linse developed the use of neural networks for aerodynamic modeling mentioned above [12].

ANNOTATED BIBLIOGRAPHY OF 1993-1994 PUBLICATIONS

1. D. A. Stratton and R. F. Stengel, "Robust Kalman Filter Design for Predictive Wind Shear Detection," *IEEE Trans. Aerospace and Electronic Systems*, Vol. 29, No. 4, Oct. 1993, pp. 1185-1194.

Severe, low-altitude wind shear is a threat to aviation safety. Airborne sensors under development measure the radial component of wind along a line directly in front of an aircraft. In this paper, optimal estimation theory is used to define a detection algorithm to warn of hazardous wind shear from these sensors. To achieve robustness, a wind shear detection algorithm must distinguish threatening wind shear from less hazardous gustiness, despite variations in wind shear structure. This paper presents statistical analysis methods to refine wind shear detection algorithm robustness. Computational methods predict the ability to warn of severe wind shear and avoid false warning. Comparative capability of the detection algorithm as a function of its design parameters is determined, identifying designs that provide robust detection of severe wind shear.

2. S. S. Mulgund and R. F. Stengel, Target Pitch Angle for the Microburst Escape Maneuver, *J. Aircraft*, Vol. 30, No. 6, Nov.-Dec. 1993, pp. 826-832.

Commuter and general aviation aircraft face no less a threat from microburst wind shear than do large jet transports, yet most studies of wind shear encounter have neglected them. The effects of microburst wind shear on a propeller-driven commuter aircraft are considered here. Recovery performance of a commuter-type aircraft in a microburst encounter is examined using a constant-pitch-attitude strategy and flight-path optimization. The goals are to identify a suitable target pitch angle for the escape maneuver and to determine the nature of an optimal escape maneuver for commuter aircraft. The results demonstrate that the pitch attitude that maximizes climb rate in a wind shear is strongly dependent on whether the shear is predominantly a downdraft or a horizontal shear. Simulated recoveries show that the optimal constant pitch angle depends on the altitude of encounter, the strength of the microburst, and the initial position of the aircraft relative to the microburst core. In severe wind shear encounters at very low altitude, best results are obtained at relatively low pitch angle. Excessively high target pitch angles subject the aircraft to prolonged periods near stall. Flight path optimization demonstrates that maximum ground clearance is obtained by maintaining a low pitch attitude early in the encounter followed by a gradual pitch-up that ceases when the aircraft exits the wind shear.

3. S. S. Mulgund and R. F. Stengel, Optimal Recovery from Microburst Wind Shear, *J. Guidance, Control, and Dynamics*, Vol. 16, No. 6, Nov.-Dec. 1993, pp. 1010-1017.

The flight path of a twin-jet transport aircraft is optimized in a microburst encounter during approach to landing. The objective is to execute an escape maneuver that maintains safe ground clearance and an adequate stall margin during the climb-out portion of the trajectory. A cost function penalizing rate of climb deviations from a nominal value and the rate of elevator deflection produces qualitatively good results in a variety of microburst encounters. The optimal maneuver is a gradual pitch-up that ceases near the core of the microburst, followed by a slight reduction in pitch attitude in the tailwind area of the microburst. A minimum airspeed constraint in the optimization prevents excessive airspeed loss in very severe microbursts. The aircraft equations of motion include short-period dynamics, so that the optimization solves directly for the control surface deflections required to achieve the optimal flight paths.

4. S. S. Mulgund and R. F. Stengel, "Aircraft Flight Control in Wind Shear Using Partial Dynamic Inversion," *Proceedings of the 1993 American Control Conference*, San Francisco, June 1993, pp. 400-404.

A flight control law based on partial inversion of the longitudinal dynamics of a twin-jet transport aircraft is presented. The controller is partitioned into a slow-time-scale and a fast-time scale to simplify its design. Three types of controllers are developed: airspeed/climb rate, groundspeed/climb rate, and throttle/climb rate. For microburst encounters during approach to landing, it is found that a combination of airspeed and groundspeed regulation is quite effective for controlling the flight path to touchdown. Regulation of groundspeed to a nominal value in the performance-increasing region of the microburst prevents an inadvertent reduction in thrust, while regulation of airspeed to a nominal value in the performance-decreasing area of the microburst prevents excessive airspeed loss. The throttle/climb rate controller is used for aborted-landing encounters. The combination of groundspeed and airspeed control is used until the decision is made to abort the landing, at which point maximum throttle and a specified positive climb rate are commanded.

5. D. R. Spilman and R. F. Stengel, "Jet Transport Response to a Horizontal Wind Vortex," *AIAA 31st Aerospace Sciences Meeting*, Reno, AIAA Paper No. 94-0811, Jan. 1994.

The dynamic response of a twin-jet transport aircraft encountering a single-axis wind vortex on final approach to landing is investigated. Severe performance degradation and possible ground impact may result from a low-altitude encounter

with a wind rotor, which is formed by strong winds that flow over a mountain range and roll up on the leeward side of the mountain. The simulation makes use of the similarities between flow induced over the aircraft surfaces by angular rates and the flow induced by a wind gradient. A single-axis vortex model approximates the wind velocity field. Dynamic simulations illustrate the effects of vortex strength, vortex length, lateral entry position, vertical entry position, and encounter incidence angle on the aircraft roll response parameters. Results show that maximum roll rate and roll angle increase proportionally with vortex strength and vortex length, until a "saturation length" is reached. Roll response is highly dependent on entry location: changes in lateral entry position affect maximum roll angle while changes in vertical entry position affect maximum roll rate. Peak roll rate and roll angle obtain their largest values at near-zero incidence angles. The response is highly dependent on the initial conditions of the encounter -- even small variations cause significant changes in aircraft roll response.

6. C. I. Marrison and R. F. Stengel, "The Use of Random Search and Genetic Algorithms to Optimize Stochastic Robustness Functions," *Proc. 1994 American Control Conference*, Baltimore, Jun. 1994.

Stochastic robustness synthesis is a framework for designing practical control systems. It uses Monte Carlo simulation to evaluate the quality of candidate designs, and it searches a parameter space to find the best one. The global minimum of a probabilistic criterion function must be found, ideally with a minimum number of evaluations. This paper examines two approaches to minimizing the probabilistic function: random search and a genetic algorithm. The genetic algorithm is similar to previously published algorithms but has several modifications to improve its performance, most notably a clustering analysis at the beginning of each generation. Statistical tools are incorporated in the search algorithms, allowing intelligent decisions to be based on the "noisy" Monte Carlo estimates. Performance of the two methods is demonstrated by application to a 24-dimensional test function. The genetic algorithm is shown to be significantly better than the random search for this application. The genetic algorithms is then used to design compensators for a benchmark problem, producing control laws with excellent levels of stability and performance robustness.

7. R. F. Stengel and J. P. Wangermann, "Air Traffic Management as Principled Negotiation Between Intelligent Agents," in *Machine Intelligence in Air Traffic Management*, AGARD-CP-538, Neuilly-sur-Seine, Oct. 1993, pp. 5-1 to 5-10.

Air transportation provides the backbone for passenger transport over moderate to long distances in the U.S. and much of the world, and it is becoming an increasingly important mode for short-range travel and cargo transport as well.

There is a growing demand for use of available airspace and a heightened concern for on-time performance. Demand frequently exceeds available capacity of the airspace system, causing flight delays, negative economic impact, and passenger inconvenience [1, 2]. New technologies are emerging that will make flight operations both simpler and more complex. On the one hand, advances hold promise for increasing the productivity, reliability, and safety of the air transportation system. On the other, advances in technology introduce uncertainty, increase human workload (if not properly implemented), increase the potential for dispute, and present new challenges for both certification and day-to-day operations. This paper presents a concept for an *Intelligent Aircraft/Airspace System (IAAS)* that could be a focal point for developing air traffic management in the coming decades. The *IAAS* would integrate the capabilities of all ground-based and airborne components of the system (identified as *Intelligent Agents*) in order to provide increased capacity and maintained or improved safety. *Principled Negotiation* is proposed as a framework for interactions between intelligent agents.

8. R. F. Stengel, "Toward Intelligent Flight Control," IEEE *Trans. Systems, Man, and Cybernetics*, Vol. 23, No. 6, Nov.-Dec. 1993, pp. 1699-1717.

Flight control systems can benefit by being designed to emulate functions of natural intelligence. Intelligent control functions fall in three categories: declarative, procedural, and reflexive. Declarative actions involve decision-making, providing models for system monitoring, goal planning, and system/scenario identification. Procedural actions concern skilled behavior and have parallels in guidance, navigation, and adaptation. Reflexive actions are more-or-less spontaneous and are similar to inner-loop control and estimation. Intelligent flight control systems will contain a hierarchy of expert systems, procedural algorithms, and computational neural networks, each expanding on prior functions to improve mission capability, to increase the reliability and safety of flight, and to ease pilot workload.

9. R. F. Stengel, "Intelligent Flight Control Systems," in *Aerospace Vehicle Dynamics and Control*, Press, Oxford, UK, 1994, pp. 33-80.

The capabilities of flight control systems can be enhanced by designing them to emulate functions of natural intelligence. Intelligent control functions fall in three categories. *Declarative* actions involve decision-making, providing models for system monitoring, goal planning, and system/ scenario identification. *Procedural* actions concern skilled behavior and have parallels in guidance, navigation, and adaptation. *Reflexive* actions are spontaneous, inner-loop responses for control and estimation. Intelligent flight control systems learn knowledge of the aircraft and its mission and adapt to changes in the flight environment. Cognitive models form an efficient basis for integrating "outer-loop/inner-loop" control functions and for developing robust parallel-processing algorithms.

10. D. Linse and R. F. Stengel, "Identification of Aerodynamic Coefficients Using Computational Neural Networks," *J. Guidance, Control, and Dynamics*, Vol. 16, No. 6, Nov.-Dec. 1993, pp. 1018-1025.

Precise, smooth aerodynamic models are required for implementing adaptive, nonlinear control strategies. Accurate representations of aerodynamic coefficients can be generated for the complete flight envelope by combining computational neural network models with an Estimation-Before-Modeling paradigm for on-line training. A novel method of incorporating first-partial-derivative information is employed to estimate the weights in individual feedforward networks for each coefficient. The method is demonstrated by generating a model of the normal force coefficient of a twin-jet transport aircraft from simulated flight data, and promising results are obtained.

11. S. S. Mulgund, *Longitudinal Aircraft Flight in Microburst Wind Shear*, Ph. D. Thesis, Princeton University, MAE-1995-T, June, 1994.

Severe low-altitude wind variability poses a significant hazard to aircraft in the terminal area. Longitudinal control strategies to improve flight safety in microburst wind shear are developed using deterministic trajectory optimization and feedback control based on the aircraft's nonlinear inverse dynamics. Optimal state estimates for feedback are computed using extended Kalman filtering.

12. D. J. Linse, *System Identification for Adaptive Nonlinear Flight Control Using Neural Networks*, Ph. D. Thesis, Princeton University, MAE-1997-T, June 1994.

Nonlinear flight control strategies require precise, smooth representations of the airplane's aerodynamic model. Most nonlinear system identification techniques do not provide smooth models across a wide range of flight conditions. Using computational neural networks -- biologically inspired, massively parallel computational structures -- to perform generalized spline function approximation provides an excellent building block for identification. A novel training method incorporates first-partial-derivative information in the network's learning algorithm to constrain the network function space and to aid in selecting the weights in the network. An estimation-before-modeling structure provides a framework for generating on-line training information. Identification of a normal-force model for a twin-jet transport airplane demonstrates the technique. Independent maneuvers validate the network's performance in untrained regions of the flight envelope. They are adaptive, they learn from examples, and they can provide excellent approximation for a large class of functions.

INVENTIONS

No patents or inventions are reported under this grant. Our focus has been on the development of engineering methods and scientific knowledge.